

Temperature Of Solar Cells With Regard To Photoactive And Non-Photoactive Light Absorption In Concentrator PV Modules

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Abstract. A new method has recently been proposed by us for accurate measurement of the solar cell temperature in any operational regime, in particular, at a maximum power point (MPP) of the I-V curve (T_{p-n}^{MPP}). For this, fast switching of a cell from MPP to open circuit (OC) regime is carried out and open circuit voltage V_{oc} is measured immediately (within about 1 millisecond), so that this value becomes to be an indicator of T_{p-n}^{MPP} . In the present work, we have considered a practical case, when a solar cell is heated not only by absorption of light incident upon its surface (called “photoactive” absorption of power), but also by heat transferred from structural elements surrounding the cell and heated by absorption of direct or diffused sunlight (“non-photoactive” absorption of power with respect to a solar cell). This process takes place in any concentrator module with non-ideal concentrators. Low overheating temperature of the p-n junction (or p-n junctions in a multijunction cell) is a cumulative parameter characterizing the quality of a solar module by the factor of heat removal effectiveness and, at the same time, by the factor of low “non-photoactive” losses.

Keywords: III-V solar cells, Concentrator modules, Temperature measurements.

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INTRODUCTION

In solar concentrator modules, cells operate at high optical power density [1]. For this reason, the problem of residual heat removal is one of key problems at optimization of module structure. Proper thermal managements are of great importance in the module design. An indicator for success in the managements is a low overheating temperature of the solar cells (SCs) with respect to the ambient temperature in operational conditions at electrical loading in the maximum power point (MPP) of the I-V curve. The open circuit voltage (V_{oc}) is a good indicator of cell temperature, if the temperature coefficient for it is preliminary measured in the pulse regime of illumination at a given photocurrent density [2]. Unfortunately, the V_{oc} value as a temperature indicator gives substantially higher temperature in MPP of a highly efficient cell, when a considerable part of power is dissipated in the external load [3].

A simple procedure for determining overheating temperature of the p-n junction area in a SC with respect to the ambient temperature in regime of connection to an electrical load has been proposed in

[4]. The procedure consists in measuring the V_{oc} value just after the moment of a fast switching from the operational mode to the open circuit mode. Used is the circumstance that the SC chip temperature is practically not changing at the cost of the material heat capacity during the first millisecond at instant disconnection from the external load. Measured in such a way V_{oc} value should be compared with that corresponding to ambient temperature for calculating the p-n junction overheating temperature.

Unfortunately, at outdoor characterization of the concentrator modules of meter sizes, there exists a problem consisted in uncertainty in initial cell V_{oc} values at a definite ambient temperature and a definite photocurrent. Indeed, the cells change their temperature very quickly and uncontrollably when illumination starts [4]. Proposed in the present work method eliminates this uncertainty allowing for determination of the real overheating for cells in a concentrator module. In addition to voltage measurements, the absolute temperatures T_{ext} of any of the external structural element near to a cell are measured in MPP and OC conditions. In analytical equations, the linear relations between ΔT and ΔV_{oc} increments are taken into account. Cell over-heating

temperature is considered as consisting of two items, one of which (“photoactive”) characterizes the heat sink efficiency from the cell chip, and another one (“non-photoactive”) characterizes degree of the “non-idealities” in a module structure.

The method was verified in indoor investigations of the single -junction AlGaAs/GaAs cells under CW laser illumination.

EVALUATION OF THE CELL OVER-HEATING TEMPERATURE

In the work we are considering such a case, when solar cell is heated not only by absorption of light incident upon its surface (called a “photoactive” absorption of power). As a rule, heat power may be transferred to a cell from module structural elements surrounding the cell and heated at absorption of direct or diffused sunlight (“non-photoactive” absorption of power regarding to solar cell). This process takes place in any concentrator module with non-ideal concentrators. At the beginning we consider only the case of “photoactive” cell thermal load.

Fig.1 shows the schematic of measuring the parameters by the procedure in conditions of continuous illumination of a solar cell.

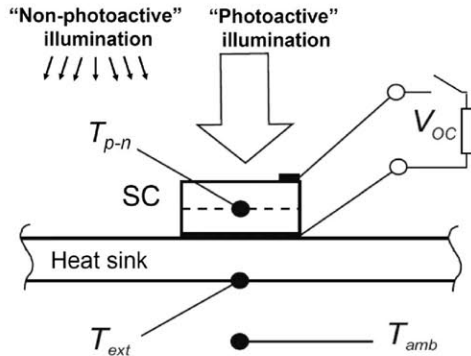


FIGURE 1. Schematic of measuring the parameters by the procedure in conditions of continuous illumination of a solar cell.

The light flux is directed to the photo-receiving area of a cell mounted on a heat-sinking element. The voltage V_{OC} appears on the cell contacts. If a load resistance is connected to the cell, a part of the photocurrent flows in the circuit, and a part of the power absorbed in the cell is transferred to the load owing to the arising voltage drop. The cell p-n junction temperature T_{p-n} depends on the illumination intensity and on the conditions of power transfer to the load (if it is connected to the cell). Also, it depends on the conditions of heat transfer to the heat-dissipating element (these conditions determine

temperature of any heated part of the module T_{ext}) and, finally, on the ambient temperature T_{amb} .

Assume that “non-photoactive” illumination is absent. The required p-n junction overheating temperature in conditions of the thermal balance at any regime of connecting the cell to the external load is the temperature difference:

$$\Delta T_{p-n} = T_{p-n} - T_{amb}. \quad (1)$$

It is known that, at the fixed density of the current generated in a cell, the $V_{OC} = f(T)$ dependence is, practically, a linear function in the near to room temperature range [2]. For this reason, one can write that:

$$\Delta T_{p-n} = \frac{1}{a \cdot 10^{-3}} (V_{OC} - V_{OC}^{amb}), \quad (2)$$

where a [mV/°C] – temperature coefficient of V_{OC} at a given current density; V_{OC} and V_{OC}^{amb} – open circuit voltages at balanced temperature and at the ambient temperature, correspondingly.

Owing to the linear dependence of the open circuit voltage on temperature and proportional dependence of module overheating temperature ΔT_{ext} on the total power absorbed in a PV module, the V_{OC}^{amb} value in coordinates “Temperature – Voltage” lies on the continuation of a straight line connecting the values of V_{OC} and V_{OC}^{MPP} at $T = T_{amb}$. The corresponding graphical plot is presented in Figure 2, where the V_{OC}^{MPP} value is measured during a short time period just after switching-off the external load, and the T_{ext}^{MPP} value – in the period of achieving the system thermal balance before this switching. Also, it can be shown that in the analytical form V_{OC}^{amb} value may be calculated by (3).

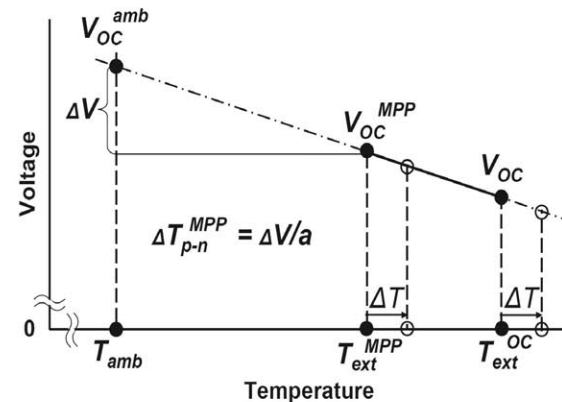


FIGURE 2. Graphical construction of the dependence of the cell open circuit voltage on temperature T_{ext} for determining V_{OC}^{amb} value. Also, (2) is shown for the case of ΔT_{p-n} determination at MPP point of the cell I-V curve. At “non-photoactive” absorption of power, corresponding points of measured voltages and temperatures shift to the right by ΔT value.

$$V_{OC}^{amb} = \frac{V_{OC}^{MPP}(T_{ext}^{OC} - T_{amb})}{T_{ext}^{OC} - T_{ext}^{MPP}} V_{OC}(T_{ext}^{MPP} - T_{amb}) \quad (3)$$

In the case of presence of the “non-photoactive” illumination, temperature of the PV module body and temperature of the cell p-n junction will be increased by ΔT value in both MPP and OC conditions (see Figure 2). Nevertheless, it can be shown again that the V_{OC}^{amb} value is calculated by the same formula (3), as it took place without “non-photoactive” illumination.

VERIFICATION OF TEMPERATURE EVALUATION PROCEDURE

In the experiments on verification of temperature evaluation procedure for p-n junctions in PV cells, single-junction AlGaAs/GaAs cells at CW laser illumination have been used [5]. A reason for this was that in indoor environment it is possible to simulate stable conditions for both “photoactive” and “non-photoactive” illumination. Also, relatively small photoactive cell area may be opened practically instant for illumination by a mechanical shutter. Therefore, the V_{OC}^{amb} value can be measured directly. The latter circumstance allows comparing measured V_{OC}^{amb} value with that calculated by (3).

An analog-to-digital device has been developed for measurements, a simplified circuit of which is presented in Figure 3. The device was ensuring measurements of voltage and current in the regime of a memory oscilloscope. Also, the regime of connecting a PV cell to the external load could be varied.

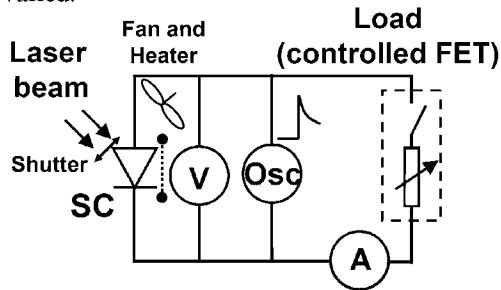


FIGURE 3. Functional diagram of the measurement equipment: electronic board ensures I-V measurements in the memory oscilloscope regime, regulating at the same time and switching off in a fast manner the external load [4]; heater, which imitates “non-photoactive” illumination; mechanical shutter, which ensures fast opening the cell photoactive area for illumination.

By primary V_{OC} measurements under pulse illumination, it has been found that cell p-n junction temperature practically does not rise during first

millisecond after starting illumination, if a cell specimen is soldered to a copper heat spreader and the photocurrent density does not exceed about 10 A/cm². In Figure 4, temporal characteristics of the mechanical shutter and the electronic switch are shown ensuring correct measurements of both V_{OC}^{amb} and V_{OC}^{MPP} values.

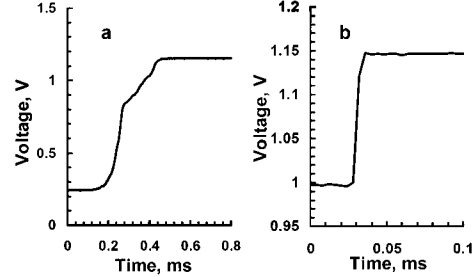


FIGURE 4. (a)—oscillogram of the open circuit voltage in a AlGaAs/GaAs PV cell in opening a mechanical shutter; (b)—oscillogram of changeover from the MPP regime to the open circuit one realized at FET operation.

In Table 1, the indoor experimental conditions and the results of measurements and calculations are shown for the temperature (measured by the Pt100 resistors) and open circuit voltage values for a single-junction AlGaAs/GaAs cell at CW laser illumination.

TABLE 1. Parameters measured and calculated in the experiments. The conditions are as follows: laser beam $\lambda=808$ nm; $P=0.71$ W; one-junction 4×4 mm² AlGaAs/GaAs cell soldered to a copper holder $30 \times 30 \times 3$ mm in size; $a = -1.51$ mV/°C at $j_{ph} = 2.71$ A/cm². Temperature values are in °C; voltage values are in Volts.

Parameter	Cooling by air convection	Heating of the holder	Cooling by blow-off
T_{amb}	23.0	23.3	22.7
T_{ext}^{amb}	23.02	23.28	22.48
T_{ext}	—	35.95	—
T_{ext}^{MPP}	36.78	47.64	26.72
T_{ext}^{OC}	45.58	56.01	29.94
V_{OC}^{MPP}	1.12979	1.11303	1.14573
V_{OC}	1.11526	1.09936	1.14009
V_{OC}^{amb}			
calculated	1.15251	1.15277	1.15277
measured	1.15265	1.15239	1.15272
Accuracy at T evaluation	-0.09	+0.25	+0.03
ΔT_{p-n}^{MPP}			
calculated	15.1	26.4	4.7
ΔT_{p-n}^{OC}			
calculated	24.7	35.4	8.5

The ambient temperature T_{amb} was registered with precision of the first decimal place, the other temperatures – of the second decimal place. Voltage values for the single-junction AlGaAs/GaAs PV cell were being measured with the highest possible accuracy for estimating a probable error in finding V_{OC}^{amb} at a direct measurement and at calculations by formula (3). After this, ΔT_{p-n}^{OC} and ΔT_{p-n}^{MPP} values were calculated by formula (2). In the latter case this formula was used in the view (4), where V_{OC} value was replaced by V_{OC}^{MPP} :

$$\Delta T_{p-n}^{MPP} = \frac{1}{a10^{-3}} (V_{OC}^{MPP} - V_{OC}^{amb}) . \quad (4)$$

A good fit of the rated V_{OC}^{amb} values to the directly measured ones in the experiments on converting laser radiation is noteworthy. This conclusion may be extended for all three modifications of the experiments: (i) at “normal” cooling of a cell holder by air convection (simulation of purely “photoactive” illumination); (ii) at heating of the cell holder (simulation of “photoactive” + “non-photoactive” illumination); (iii) at intensive cooling with the help of a fan (simulation of the operational conditions of solar modules taking frequently place outdoors). It should be noted that indoor results of Table 1 have been aimed at comparison of the directly measured and calculated V_{OC}^{amb} values in “ideal” environmental conditions. But even in this case there exists certain discrepancy between OC voltage values and initial T_{amb} values. A reason for this is actual instability of the ambient temperature during long-term experiments, when balance in thermal conditions has to be achieved at any stage of measurements. It seems that the same type of errors in OC voltage and temperature values is typical also for outdoor experiments on converting solar radiation in large-in-size modules. Also, there exists probable uncertainty in choosing a coefficient at transformation of the voltage values into temperature ones. This coefficient should correspond to the photocurrent density of the cells in a tested device. As the special experiments with pulse illumination have shown, at the error in determining the photocurrent density, for instance, in two times, the error in a value is only about 6%. Of course, it is only the methodological error, which does not extend to probable cases of non-stable and non-uniform power incoming and heat removing in the tested solar modules.

CONCLUSION

The elaborated procedure for the p-n junction overheating temperature evaluation in the PV cells

operating in the MPP regime consists in measuring two open circuit voltage values and three values of temperature on the outer module surface near to the cell. The only “special” measurement in this case is the measurement of V_{OC} during a short time after fast switching-off the external resistance. The carried out indoor verification of the method at conversion of laser radiation has shown a possibility to realize a quite small error of about $0.1 \div 0.2^\circ\text{C}$ in obtained temperature. This error is associated with possible uncertainty in the open circuit voltage temperature coefficient, which, in turn, depends on the photocurrent density. It does not include probable effects of non-uniform power incoming and heat removing in the tested solar modules, as well as effects of non-stable environmental conditions, which may take place at outdoor experiments. Low overheating temperature of the p-n junction (or p-n junctions in a multijunction cell) is a cumulative parameter characterizing the quality of a solar module by the factor of heat removal effectiveness and, at the same time, by the factor of low “non-photoactive” losses.

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